

Accelerated Charcoal Briquette Production: Innovative Drying Technology for Performance Assessment and Energy Consumption

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ABSTRACT

Currently, the process of charcoal briquette production comprises three primary stages and typically spans 5–7 days. Each stage aims to maximize the thermal efficiency of the final product. The initial phase involves the preparation of raw materials, including the formulation of mixtures and the selection of components or treatments that enhance the calorific value of the briquettes. The second stage focuses on high-yield briquette formation, optimizing compaction and shaping techniques to produce charcoal briquettes in large quantities. The final, most time-consuming stage is the drying process, which significantly influences the overall production cycle. This study aims to design an accelerated high-temperature drying system to reduce the processing time for charcoal briquettes, specifically targeting moisture contents between 25–30% post-formation. The proposed system is designed to handle 50 kg of briquettes per batch, arranged in five layers (10+ kg per layer, 5 layers total), and utilizes three infrared burners, measured and controlled by a PID (Proportional-Integral-Derivative) control system. The parameters are tailored based on the drying behavior of charcoal to achieve a final moisture content of less than 8%, in compliance with industry standards. Experimental results indicate that the five-layer drying chamber effectively generates uniform heat distribution and enhances internal air circulation, enabling consistent and thorough drying. The drying sequence starts from the bottom layer and progresses upward. Among the tested conditions, drying at 150°C demonstrated the highest efficiency, providing the most suitable drying time and the lowest fuel consumption rate, thereby improving both energy efficiency and production throughput.

1. Introduction

Thailand has experienced a steady increase in national energy consumption over the past decade, with electricity demand rising sharply during the summer due to elevated cooling requirements across residential, commercial, and industrial sectors. National energy balance assessments indicate that domestic energy production remains insufficient to meet this growing demand, resulting in continued reliance on imported energy and increased exposure to price volatility, supply insecurity, and geopolitical risks. In response, the Ministry of Energy implemented the Alternative Energy Development Plan (AEDP) 2015–2036 (Fig. 1), which sets a target for renewable energy to account for 30% of total final energy consumption by 2036, up from 25% under the 2012–2021 plan [1].

Within this framework, biomass is identified as a key contributor to the thermal energy sector, with a projected share of 22,100 kTOE, equivalent to approximately 56.10% of total renewable energy consumption. This highlights the strategic role of biomass as a locally available, low-carbon resource that supports waste utilization, rural income generation, and reduced environmental impacts compared with fossil fuels [2–4]. Among biomass-based fuels, charcoal briquettes produced from agricultural residues—such as coconut shells and other lignocellulosic wastes—are widely manufactured and consumed in Thailand, particularly for household cooking and small commercial applications.

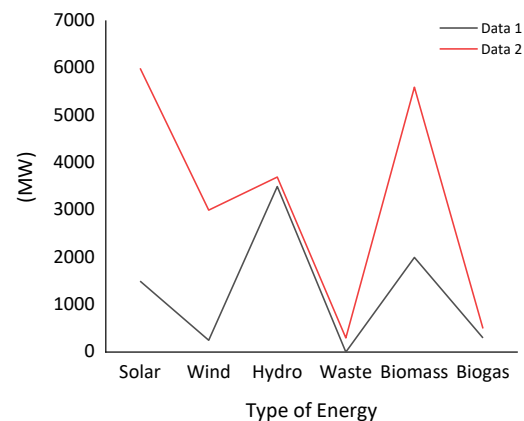


Fig. 1 Alternative Energy Development Plan (AEDP 2036).

Biomass energy is derived from organic materials that store solar energy through photosynthesis and release it through thermal, biochemical, or physicochemical conversion processes. In Thailand, biomass is a particularly important renewable energy resource due to its abundance, low cost, and widespread availability in agricultural and rural areas. Major biomass resources include agricultural residues, forestry by-products, and agro-industrial wastes, which collectively contribute to national energy security, waste valorization, and greenhouse gas mitigation [5–7].

Biomass in Thailand is commonly classified into woody and non-woody types. Woody biomass—such as coconut shells, palm shells, rubberwood residues, rice husks, and bagasse—is especially attractive for solid fuel applications because of its relatively high calorific value and stable combustion characteristics. These materials are widely utilized in industrial boilers, combined heat and power systems, and the production of charcoal and charcoal briquettes. Non-woody biomass, including herbaceous crops and organic wastes, typically exhibits higher moisture content and is more suitable for biochemical conversion pathways [8–12]. Among biomass-derived solid fuels, charcoal briquettes produced from locally available residues—particularly coconut shells—are extensively manufactured and consumed in Thailand for household cooking and small commercial applications. Previous studies conducted in the region have largely focused on raw material selection, binder type, compaction pressure, and combustion performance of charcoal briquettes. However, the drying process, which critically determines moisture content, mechanical strength, energy efficiency, and production throughput, has received limited systematic investigation. Conventional drying practices in Thailand predominantly rely on natural sun drying or low-cost solar methods, which are highly weather-dependent, require long processing times, and constrain large-scale or continuous production. These limitations highlight a significant research gap in the optimization of drying technology for charcoal briquettes under controlled conditions. Therefore, this study focuses on the development and performance analysis of an accelerated drying process for charcoal briquettes produced from coconut shell charcoal. By emphasizing drying kinetics, energy consumption, and system performance, this work provides practical insights that address the shortcomings of existing practices and support more efficient, reliable, and scalable charcoal briquette production in Thailand.

The calorific value of biomass is primarily governed by its chemical composition, particularly lignin, cellulose, moisture, and ash contents. Biomass with high lignin content, such as wood-based residues, generally exhibits higher calorific values, whereas materials with elevated moisture or ash content, including animal manure, display lower energy potential [13]. To improve fuel quality, biomass densification through briquetting has been widely adopted as an effective physical conversion method, especially for materials characterized by low bulk density, high moisture content, and heterogeneous composition. In Thailand, charcoal briquettes produced from locally available biomass—such as coconut shells and other agricultural residues—are extensively used for household and small commercial applications. Densification technology addresses key limitations of raw biomass by increasing bulk density, improving handling and combustion behavior, and producing uniform fuel products with enhanced energy efficiency and storability [14]. However, despite its widespread adoption, commercial briquette production continues to face critical challenges across three main stages: raw material preparation, compression, and drying. Among these stages, the drying process remains the most difficult to control and represents the principal bottleneck limiting production capacity. Previous studies and local production practices have largely emphasized briquetting pressure, binder composition, and calorific value, while the drying stage has often relied on low-cost methods such as sun drying, wind drying, or parabolic solar domes [15–17]. These approaches typically require 3–5 days for sufficient moisture reduction and extend the overall production cycle to approximately 5–7 days, making them highly dependent on weather conditions and unsuitable for continuous or large-scale production [18–23].

Table 1 Calorific values of different types of biomass.

Biomass	Unit	Calorific value (MJ/kg)
Corn cobs	kg	19.00
Palm fibers	kg	20.17
Rubber wood	kg	18.83
Sawdust	kg	20.88
Bamboo	kg	15.52
Water hyacinth	kg	12.59
Pig manure	kg	11.27
Chicken manure	kg	7.28

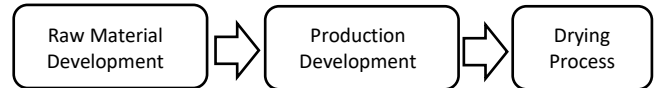


Fig. 2 Charcoal production process.

These limitations highlight the need for systematic investigation and optimization of drying technology for charcoal briquettes produced in the region. Accordingly, this study focuses on improving the drying stage to enhance production efficiency, reduce processing time, and support scalable charcoal briquette manufacturing. By addressing a critical gap in existing research, the proposed approach contributes to more reliable, energy-efficient, and commercially viable biomass fuel production.

In briquette charcoal production, drying systems or drying processes currently employed can be classified into two main categories. The first is natural open-air drying, which relies on solar radiation and ambient airflow to remove moisture. This method requires a relatively long drying period (approximately 3–7 days), depending on seasonal conditions, and necessitates storage of the charcoal during nighttime. The second category involves forced drying or technology-assisted drying methods. Among these, large-scale parabolic solar dome dryers are commonly used due to their ability to process large quantities per batch. Although this approach exhibits relatively good drying efficiency, it remains limited by the availability of solar energy, which is restricted to daytime operation. As a result, the drying process typically requires 2–3 days and is still influenced by seasonal variations. In contrast, the developed drying process presented in this study accommodates a smaller batch size than parabolic dome drying systems but achieves a significantly shorter drying time. Moreover, it allows for an increased number of drying cycles based on user demand. Importantly, the performance of the proposed system is not affected by moisture content, ambient airflow, or seasonal conditions, demonstrating improved operational flexibility and reliability.

Therefore, this study focuses on the development of a high-temperature drying oven to accelerate the charcoal briquette production process. The quality of the briquettes and the efficiency of the drying method were systematically evaluated to assess their suitability and viability for commercial-scale production.

2. Experimental detail

2.1 Drying Process Design

The design of drying systems for charcoal briquettes is critical in the briquetting process, which enhances the material density, reduces the moisture content, and alters the size and shape of the biomass to facilitate storage, transportation, and energy conversion.

Biomass can be densified into various fuel forms, such as pellets, cubes, extruded logs, and bales. Among these, briquettes and pellets are the most used formats for energy production, with the choice depending on the feedstock characteristics and the intended application. Currently, there are two primary types of densified fuel bars: 1. Charcoal briquettes are produced by carbonizing biomass or waste material and then compressing it into briquettes. Alternatively, pre-compressed fuel bars can be subjected to pyrolysis to produce charcoal briquettes. 2. Green fuel briquettes – made from raw biomass or organic waste, compressed into briquettes without carbonization. These can be used directly as renewable, solid fuels.

The raw materials used for producing compressed fuel pellets primarily consist of various agricultural residues and post-harvest biomass, all of which possess significant potential for bioenergy application. The main sources include the following: 1) Agricultural residues and plant by-products, such as sawdust, bagasse, rice husks, corn cobs, sugarcane leaves and tops, stalks, and rhizomes. These materials typically have low bulk densities, making them challenging to collect and transport. Converting them into compressed fuel pellets not only increases their energy density and facilitates logistics but also adds economic value to otherwise underutilized natural resources. 2) Invasive and wild-growing vegetation, including common weeds that proliferate in cultivated lands or fallow areas across diverse soil types. Although often considered undesirable, many of these species have viable energy potential when they are processed into biofuels. 3) Industrial by-products, such as spoiled flour from food processing plants, distillery waste from alcohol production, industrial sludge, and sludge from wastewater treatment facilities. When properly treated and densified, these materials can serve as alternative fuel sources. 4) Municipal solid waste (MSW) – When converted into refuse-derived fuel (RDF), MSW offers a dual benefit: mitigating the growing issue of solid waste accumulation and contributing to energy generation. Utilizing MSW for fuel pellet production supports both energy security and environmental sustainability.

2.2 Fuel pelletizing principle

The fundamental principle of fuel pellet compression involves applying pressure to a mass of fine particles, causing them to compact and bond into a cohesive solid. This process is based on the concept that all matters are influenced by attractive intermolecular forces that facilitate particle adhesion. The bonding strength between particles is inversely proportional to the square of the distance between them. These forces, which arise from atomic, molecular, and interfacial interactions, play a critical role in the structural integrity of compressed pellets. A binder may or may not be used, depending on the inherent binding properties of the material, to enhance cohesion and durability.

Fuel pellet compression methods can be classified into three types based on the level of applied pressure [24-27]:

1. High-pressure pelletizing relies on increased intermolecular attraction at the interface between solid particles and surface moisture, which is primarily governed by adhesive forces. Additionally, the compression process promotes mechanical interlocking between the particles, resulting in strong structural bonds without the need for external binders. The high-pressure pelletizing technique also contributes to improved product quality by transforming the material from a dense to a high-density structure. This process reduces interparticle spacing, resulting in tighter and more durable pellets.

Furthermore, when heated, these pellets generate a high amount of heat and maintain it for a longer duration.

2. Medium-pressure pelletizing utilizes thermal softening to aid compression and is particularly effective for biomass materials rich in lignin and cellulose. When heated, lignin becomes thermoplastic, allowing the particles to soften, flow, and bind together through natural adhesion during compaction. The medium pressure pelletizing technique not only produces fuel products of moderate quality but also reduces processing time and energy costs while minimizing excessive stress on materials and machinery. This makes medium pressure pelletizing a suitable method in terms of product quality, practicality, economic benefits, and its potential for expansion into various applications.

3. Low-pressure pelletizing requires the addition of binding agents to facilitate particle adhesion and the formation of pellets. The effectiveness of this method depends on the adhesive properties of the binder, such as its viscosity, tackiness, and compatibility with the feedstock. Effective binders, such as tar or naturally sticky organic substances, promote bonding through multiple mechanisms. This pelletizing process is relatively common and widely used due to its low cost and minimal material preparation requirements. Low-pressure pelletizing requires adhesive binders to enhance interparticle bonding strength. After the pellets are pressed, they must be dried with the drying time or process depending on the moisture content at the time of palletization to increase their strength and rigidity, making them suitable for use.

- Adhesion forces between dissimilar molecules (solid-liquid interface),
- Cohesion forces between similar molecules within the binder, and
- Mechanical interlocking between particles is enhanced by the binder's film-forming ability.

The overall process of charcoal briquetting can be systematically divided into several critical stages, each of which plays a significant role in determining the quality and performance of the final product. The initial stage, material preparation, involves converting various biomass sources—such as wood chips, agricultural residues, or invasive weeds—into a fine, uniform charcoal powder. Depending on the production requirements, this powder may be combined with natural or synthetic binders, such as cassava flour, starch, or water, to enhance cohesion and moldability. This preparation stage is particularly important because it directly influences key characteristics of the finished briquettes, including bonding strength, thermal conductivity, combustion efficiency, structural integrity, and overall economic viability. In industrial-scale operations, precise material preparation is essential to ensure consistent product quality and efficient downstream processing. Moreover, any modifications or enhancements to the raw materials—such as particle size reduction, moisture adjustment, or binder incorporation—must be carefully implemented during this stage to optimize compaction, minimize production losses, and maintain uniformity across large batches. Effective material preparation thus serves as the foundation for producing high-quality, durable, and commercially viable charcoal briquettes.

The briquetting stage represents a critical phase in charcoal briquette production, during which the prepared charcoal powder and binder are transformed into compact, durable fuel forms. This process can be conducted manually or through an automated conveyor system, depending on the scale and design of the production facility. Prior to compression, the charcoal powder and binding agent are

thoroughly mixed and homogenized to ensure uniform consistency and optimal cohesion. The resulting mixture is then fed into a briquetting machine, which applies a controlled mechanical force to compress the material into uniform shapes, such as sticks or briquettes, before extruding and cutting them to the desired dimensions. Mechanically, the process involves applying a predetermined compressive pressure that increases the bulk density of the material while generating frictional heat. This internally produced heat facilitates partial drying of the briquettes and promotes the evaporation of residual moisture, often resulting in steam release during compression. Simultaneously, the binder undergoes drying and solidification, enabling the material to attain sufficient structural integrity, hardness, and dimensional stability. The final characteristics of the briquettes, including mechanical strength, combustion efficiency, and thermal performance—are directly influenced by the applied pressure, binder type, and degree of material homogenization. Overall, the briquetting process functions as a crucial transformation step, converting loosely prepared charcoal and binder into a cohesive, high-quality, and market-ready fuel product suitable for cooking, heating, or industrial applications.

The final stage in charcoal briquette production is the drying process, which is essential for reducing the residual moisture content of the briquettes, thereby enhancing their combustion efficiency, structural integrity, and long-term storage stability. When considered alongside the preceding stages of material preparation and compression, drying constitutes a critical step that substantially influences the overall production timeline. Adequate preparation of material batches is necessary to ensure consistent drying performance and avoid bottlenecks in the production line. Although the compression stage employs highly efficient machinery and can be completed relatively quickly, the drying phase is inherently the most time-intensive component, as its duration is governed by both the initial moisture content of the briquettes and the total batch volume. Consequently, the overall throughput and productivity of the briquetting process are largely dictated by the efficiency and duration of the drying operation. Optimizing this stage—through precise temperature control, airflow management, and layer arrangement—directly contributes to reducing production time, maintaining uniform briquette quality, and improving energy utilization.

2.3 Material Preparation Process

The material preparation stage in charcoal briquette production begins with carbonized coconut shells, which typically exist as irregularly shaped lumps or coarse fragments unsuitable for immediate compaction. To achieve the uniformity required for high-quality briquette formation, these materials must first undergo fine pulverization using a high-precision grinding machine. This process reduces the charcoal to a consistent, flour-like powder that ensures stable densification during molding. Prior to mixing, the powder must be thoroughly screened to remove contaminants such as metal shards, stones, and other hard particulates that could compromise briquette strength or cause mechanical wear to downstream equipment. To enhance operational efficiency and reduce processing time, producers commonly mill large batches of material, generally between 300 and 500 kg per production cycle. Once the charcoal has been ground to the target particle size, it is transferred to a mixing unit where binding agents are incorporated. In this study, tapioca flour was employed as a natural, biodegradable binder and combined with water to create a cohesive mixture. The addition of this binder increases the plasticity and structural stability of the charcoal mass, enabling smooth and uniform compaction during the briquetting process. This preparation stage

is essential for ensuring consistent product quality and reliable mechanical performance during drying and combustion.

2.4 Charcoal Briquette Production Process

In System 1, the production of charcoal briquettes begins with raw material preparation for compression. This process involves mixing finely ground charcoal powder with a binding agent and water to achieve a moldable consistency. The charcoal powder is derived from conventional carbonization processes; in this study, coconut shell charcoal was selected as the feedstock and pulverized using a high-efficiency grinder to obtain a uniform particle size. Cassava starch was employed as a natural binder and added to the charcoal powder at a predetermined ratio, with water acting as a solvent to facilitate homogenization. The starch content was approximately 20 wt%, although this proportion can be adjusted depending on raw material characteristics and desired briquette properties. The mixture was thoroughly blended using a mechanical mixer until a cohesive and pliable texture, like moist soil, was achieved. This uniform consistency is essential to ensure effective compaction and to prevent cracking or crumbling during the pressing stage. Following mixing, the prepared material was fed into a briquetting machine, where it was compressed under high pressure to form solid charcoal briquettes. The resulting briquettes typically ranged from 70 to 120 mm in length, depending on mold specifications. The produced briquettes exhibited adequate mechanical strength and dimensional uniformity, making them suitable for combustion applications in household cooking and industrial heating systems.

Figure 3(A) illustrates the overall research and production workflow for charcoal briquette manufacturing under natural drying conditions. The process begins with material preparation, in which charcoal powder obtained from conventional carbonization is prepared as the primary raw material. This is followed by charcoal briquette forming, where the powdered charcoal is mixed with a binding agent and water, homogenized, and subsequently compacted using a briquetting machine to form solid briquettes. After molding, the briquettes are subjected to natural drying, which relies on ambient solar radiation and natural airflow to reduce moisture content. In this pathway, the drying stage is carried out in open or semi-open conditions without auxiliary energy input, making the process highly dependent on environmental factors such as weather, airflow, and seasonal variation. As a result, the drying duration is relatively long and variable, which can influence production throughput and final product consistency.

Figure 3(B) presents the detailed charcoal briquette drying process employing a controlled dryer system. The process starts with raw charcoal preparation, where charcoal is crushed using a grinder to obtain fine charcoal powder. The powder is then mixed with a binder in a mixing unit and compressed into briquettes using a charcoal press. The formed briquettes are transferred into a drying room, where moisture removal is achieved under controlled conditions. Thermal energy is supplied by an infrared burner fueled by liquefied petroleum gas (LPG), which provides consistent and uniform heat distribution within the drying chamber. Hot air circulation promotes efficient moisture evaporation, while exhaust air is discharged through designated outlets to maintain stable drying conditions. Unlike natural drying, this system operates independently of ambient humidity, airflow, and seasonal changes. Although the batch capacity is smaller than that of large-scale solar dome dryers, the system significantly reduces drying time and allows for flexible operation with multiple drying cycles per day, thereby enhancing productivity and process reliability.

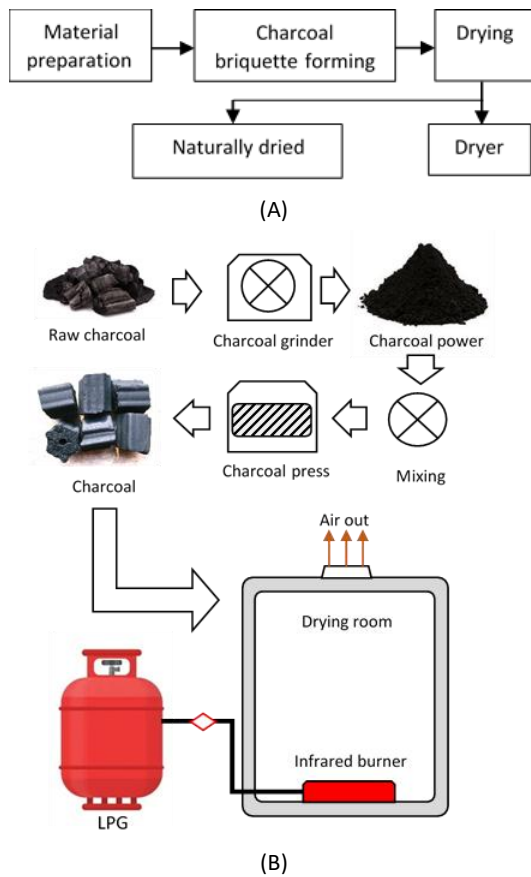


Fig. 3 Designing process (A) Study research process (B) Charcoal drying process.

2.5 Drying Process

In this case study, the drying process was carried out using a cube-shaped drying chamber designed to ensure effective heat retention and controlled airflow. The chamber was equipped with an air inlet at the bottom, where a fan generated positive internal pressure to promote uniform air distribution. An adjustable exhaust

vent was installed at the top of the chamber to regulate airflow and facilitate moisture removal. The chamber walls were constructed of metal and insulated to minimize thermal losses. Thermal energy was supplied by an LPG-fired infrared burner system installed at the base of the chamber. Temperature regulation was achieved through an LPG-based electronic control system. A centrally positioned type-K thermocouple was used to continuously monitor the internal chamber temperature, ensuring uniform thermal conditions during drying. Charcoal briquettes from System 2 were arranged on movable, multi-tiered racks inside the chamber to optimize heat transfer and airflow distribution. One side of the chamber functioned as a hinged door with a locking mechanism to prevent heat leakage during operation.

Step 1: PID-based temperature control. The drying temperature setpoint was defined using a PID controller, which received real-time temperature signals from the type-K thermocouple. The measured temperature, displayed as the process variable (PV), was continuously compared with the setpoint. When the chamber temperature dropped below the setpoint, the PID controller issued an ON/OFF control signal (220 VAC) to the ECU-GAS unit to initiate heating. The heating system was deactivated once the temperature exceeded the setpoint by 5 °C. If the temperature subsequently decreased to 5 °C below the setpoint, the heating cycle was automatically reactivated. This feedback loop maintained the drying temperature within a narrow and stable tolerance range.

Step 2: Burner activation and modulation. When an increase in temperature was required, the PID controller transmitted a 220 VAC ON signal to the ECU-GAS unit, which activated the solenoid valves supplying LPG to the three infrared burners. Burner ignition was initiated through a spark system operating for 10 s for each burner. Successful ignition was indicated by the burner status signals, while unsuccessful ignition resulted in automatic shutdown. When the setpoint temperature was reached or a temperature reduction was required, the fuel supply to the burners was closed, and the ignition system was deactivated. This modulation cycle operated continuously to maintain the desired drying temperature throughout the process, as shown in Fig. 4.

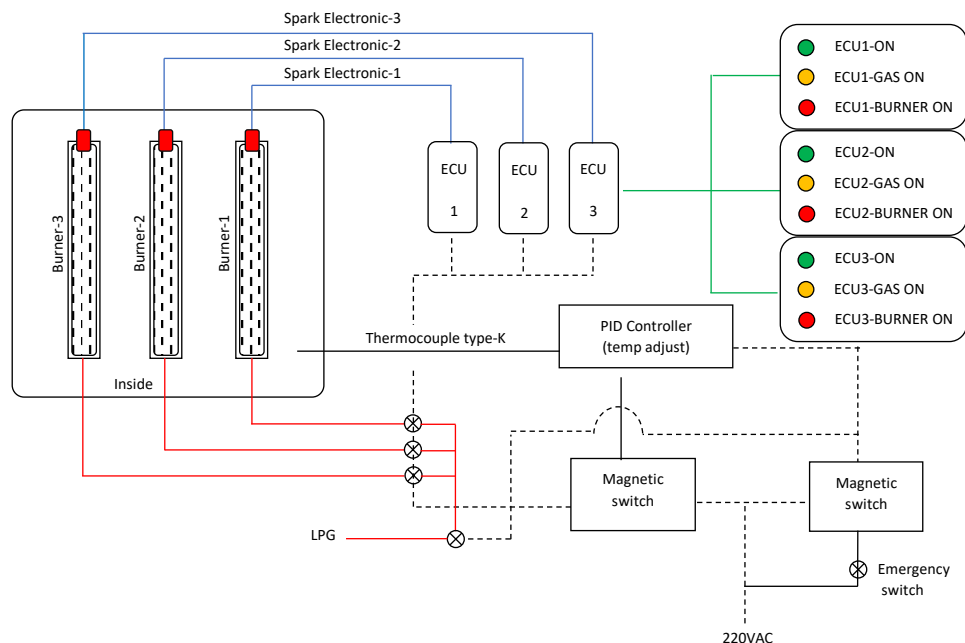


Fig. 4 Process of the temperature controller.

2.6 Moisture content analysis

Moisture content is a critical quality parameter of charcoal briquettes according to ASTM D 3173-03 [28]. Excessive moisture content reduces the effective heating value and prolongs ignition time, while excessively low moisture can lead to increased brittleness and dust formation during handling and transportation. Several studies have reported that the optimal moisture content of charcoal briquettes typically ranges between 5–10 wt%, depending on the raw material, binder type, and intended application. Moisture content is most determined using the oven-drying method at $105 \pm 2^\circ\text{C}$ until constant weight, as this method provides reliable and reproducible results for solid biofuels. This approach is consistent with international biomass and solid fuel characterization standards and is widely adopted in experimental research. Drying behavior of charcoal briquettes differs significantly from that of raw biomass due to the absence of cellulose, hemicellulose, and other thermally sensitive compounds. As a result, charcoal briquettes do not form surface hardening or moisture-impermeable films during high-temperature drying, allowing rapid moisture migration from the interior to the surface. Previous investigations have shown that controlled thermal drying methods—such as hot-air drying or infrared-assisted drying—can significantly reduce drying time compared with natural air drying, while achieving uniform moisture distribution and preserving briquette integrity. Understanding and controlling moisture content is therefore essential for optimizing briquette performance, improving energy efficiency, and enhancing the commercial viability of biomass-derived solid fuels.

3. Result and Discussion

3.1 Charcoal briquette drying development

The primary objective of the drying process is to reduce production time for compressed solid fuels, particularly charcoal briquettes, thereby improving operational efficiency and industrial throughput. Physicochemical analysis indicates that fully carbonized biomass does not contain compounds capable of forming surface films during thermal drying. Consequently, the briquettes exhibit an open, highly porous structure that facilitates internal airflow and rapid moisture migration. In addition, the briquettes possess a uniform geometry with a centrally positioned perforation, which enhances air circulation during both drying and combustion. These features enable rapid high-temperature drying without structural deformation or cracking, allowing a substantial reduction in drying time while preserving mechanical integrity.

In this study, ground coconut shell charcoal was compressed into hexagonal cylindrical briquettes with slightly rounded edges, as shown in Fig. 5. The briquettes had an outer width ranging from approximately 40 to 50 mm and incorporated a longitudinal central channel with a diameter of 10 mm to enhance convective heat transfer and promote uniform drying. The final length ranged from 85 to 100 mm, providing a standardized size suitable for handling, packaging, and combustion applications. These structural characteristics confirm that coconut-shell-based briquettes are well suited for accelerated thermal drying and efficient large-scale production. The briquette geometry and dimensions were defined by a commercially available mold widely used in Thailand for household cooking and small-scale commercial applications. The symmetrical hexagonal shape promotes uniform heat distribution and complete combustion, while the central perforation serves as an internal airflow pathway that enhances oxygen supply and combustion stability. The slightly rounded edges create interstitial gaps when briquettes are used in groups, preventing excessive stacking density and allowing additional airflow between units.



Fig. 5 Charcoal briquette in case study.

Together, these design features minimize incomplete combustion and improve overall heat output. Under typical operating conditions, briquettes of this configuration provide a steady heating duration of approximately 1–2 h, demonstrating their suitability for practical energy applications and supporting the broader adoption of biomass-derived solid fuels.

The heating system developed in this study employed liquefied petroleum gas (LPG)-fueled infrared burners arranged in a rectangular configuration corresponding to the width of the drying chamber. Three burners operated simultaneously and were equipped with an automatic ignition system to ensure stable and precise temperature control. Thermal energy generated by the burners was transferred through a combination of radiative and convective heat transfer as heated air ascended through the drying chamber. Airflow was regulated using a forced ventilation system driven by an installed fan, which distributed hot air uniformly across each drying layer and facilitated moisture removal from the briquette surfaces. The drying duration was adjusted according to charcoal mass, initial moisture content, and briquette arrangement within the chamber. The drying process was conducted in a vertically oriented system consisting of five stacked layers, with an average charcoal load of approximately 11 kg per layer. Drying commenced at the bottom layer and progressed sequentially upward until uniform moisture reduction was achieved throughout the chamber. Since the briquettes were produced from fully carbonized material in the form of hexagonal cylinders with a central perforation, the absence of cellulose and other heat-sensitive compounds prevented the formation of moisture-impermeable surface films during high-temperature drying. As a result, moisture migration from the interior to the exterior of the briquettes was not hindered, enabling effective rapid drying compared with typical agricultural products. The spatial arrangement of the briquettes played a critical role in drying efficiency. Each layer accommodated approximately 10–15 kg of briquettes, which were evenly distributed in rows of 10–12 units with sufficient spacing to maintain unobstructed airflow. The drying trays were fabricated from steel and equipped with 25×25 mm steel grates, as shown in Fig. 6(A), to minimize airflow resistance and promote uniform vertical heat transfer.

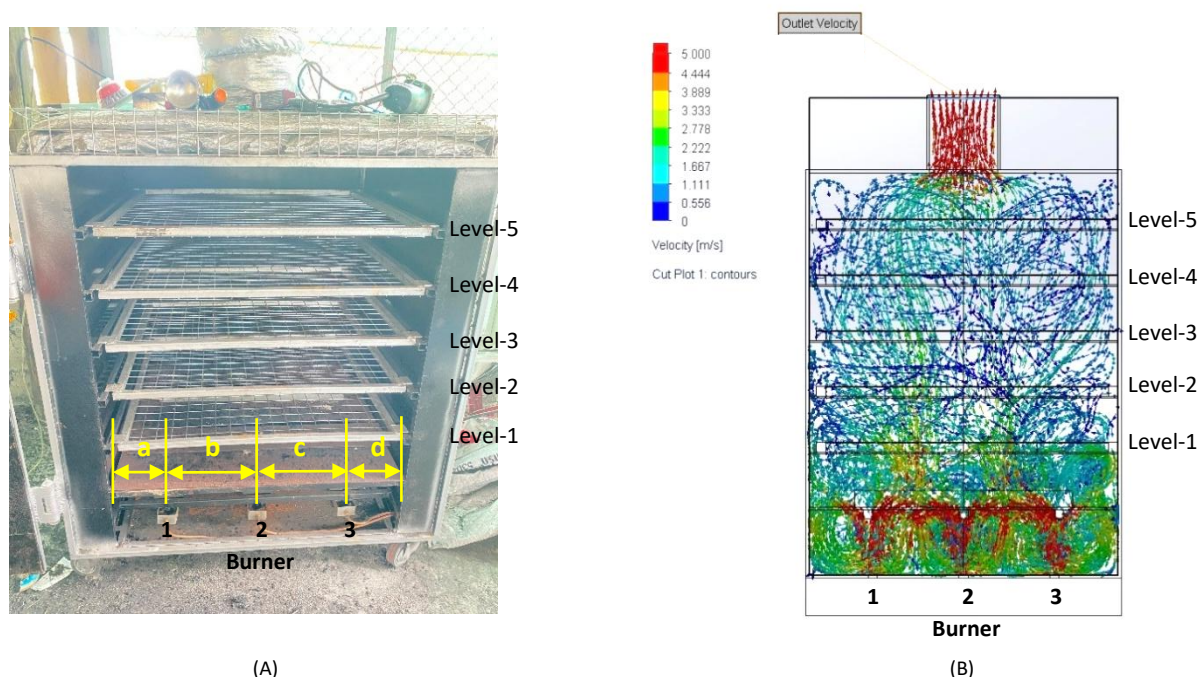


Fig. 6 Thermal process transfer inside drying oven (A) inside of drying oven (B) Thermal process transfer.

Three infrared burners were symmetrically installed at the base of the chamber to ensure even heat distribution and reduce localized overheating. A 2 mm thick steel plate was positioned between the burners and the bottom drying layer to prevent direct radiant heat exposure and to stabilize the thermal environment. The resulting heat-flow pattern, illustrated in Fig. 6(B), indicates the formation of a swirling convective airflow above the burner zone due to the presence of the steel plate. This circulating hot air ascended through successive drying layers and exited through the outlet at the top of the chamber. The configuration produced a relatively high heat flux in the lower region during the initial drying stage, where moisture release was most pronounced, before being transported upward by buoyancy-driven thermal currents. This airflow and heat-distribution strategy significantly enhanced moisture evaporation and reduced overall drying time compared with densely packed or irregular briquette arrangements.

3.2 Drying process

The temperature-rise profiles of the drying chamber under heating conditions using one, two, and three infrared burners were experimentally assessed, revealing distinct heating rates required to achieve 150 °C, as shown in Fig. 7. All burners were mounted at the base of the chamber and arranged to maintain an equivalent heating-area ratio, thereby promoting uniform thermal distribution throughout each drying cycle (50 ± 5 kg/batch). The configuration of the three-burner system necessitates equal spacing between burners to ensure consistent and homogeneous heat delivery. When operated individually, however, each burner produced comparatively lower chamber temperatures, as depicted in Fig. 7, which may have also influenced overall fuel consumption and reduced thermal efficiency.

The drying performance was evaluated using a batch of 50 ± 5 kg of raw material arranged in five drying layers, with an average weight of 11 kg per layer. The samples exhibited initial moisture content ranging from 25 % to 50 %, and the drying temperature was maintained at 150 °C. Under ambient conditions

of 27 ± 3 °C, the simultaneous operation of three infrared burners achieved the target temperature within approximately 300 min. Temperature monitoring, controlled by a PID system, was conducted at the center of the chamber. The internal drying temperature was assessed as the average of the top chamber temperature (T_{in-Top}), bottom chamber temperature ($T_{in-Bottom}$), and exhaust air temperature (T_{out}), as depicted in Fig 7.

As illustrated in Fig 6 (A), the three infrared burners operated simultaneously with a steel deflector plate installed to shield the bottom layer of charcoal from direct flame exposure. The experimental results indicate that heating the freshly produced charcoal to a drying temperature of 150 °C requires approximately 250 min, starting from an ambient temperature of 27 ± 3 °C. Fig 7 demonstrates the staged operation of the temperature control system, as evidenced by the characteristic temperature fluctuations on the graph. Notably, temperature decreases exceeding 5 °C triggered a pronounced drop, after which the system actively restored the temperature to the setpoint.

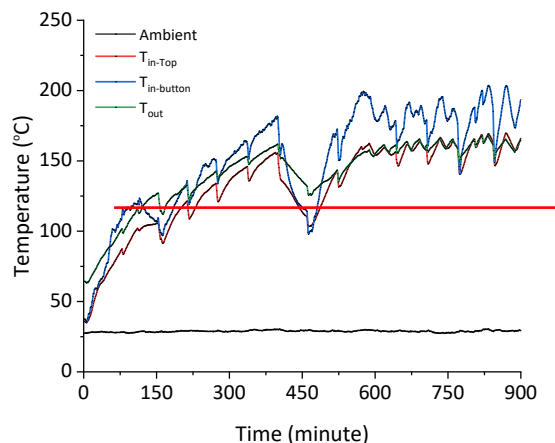


Fig. 7 Temperature grow-up inside drying oven at 150 °C setup.

Temperature deviations exceeding the predefined tolerance of $\pm 5^{\circ}\text{C}$ were attributed to the incomplete ignition of the three burners. This issue arises from the inability of the ignition system to consistently generate a flame capable of igniting LPG within the allotted 10-second ignition window. Consequently, not all burners were activated simultaneously, leading to temperature fluctuations beyond the acceptable range. During the temperature maintenance phase, specifically between 357 and 480 min, the failure to ignite all burners caused significant temperature drops. In such instances, only a single burner remains operational, resulting in a slower temperature recovery compared with scenarios in which two or all three burners are fully ignited. Consequently, despite its advantages, the LPG-fueled system exhibits inherent limitations in ignition reliability, which adversely affects the temperature stability during the drying process.

The results of the design and installation of the three infrared burner heads, arranged at specific intervals, demonstrate their collective heating characteristics, as shown in Fig 6 (A). The observed heating performance was directly correlated with the measured distances between the burner pairs a:b, c:d, and e:f.

The central burner (burner 2) generated the lowest heat output and exhibited the slowest temperature increase. This phenomenon is attributed to the spatial configuration, specifically the distance between the two burner walls [(a + b + c): (d + e + f)], which restricts the lateral heat transfer from the adjacent burners. Consequently, the heat distribution across the burner surface was uneven, limiting the chamber's ability to uniformly reach the target temperature of 150°C . Although the setpoint may eventually be attained, the prolonged heating duration and suboptimal heat dispersion result in increased LPG consumption compared to configurations utilizing multiple burners with more balanced heat distribution.

The burners positioned on the left and right (burners 1 and 3) reached the setpoint temperature of 150°C within approximately 300 min, although initial temperature fluctuations were observed. These fluctuations are likely attributable to the spatial arrangement between the burner walls [(a): (b + c + d + e): (f)], which limits the effective heat transfer across the central gap separating the two burners. This uneven heat distribution contributes to the temperature variability in the early stages. Nonetheless, both burners must operate continuously and for an equivalent duration to achieve a consistent thermal performance.

3 Burners (No. 1, 2, and 3) delivered the most stable and consistent heat output throughout the study. Although their ignition durations varied, impacting the burner lifespan and ignition reliability during temperature regulation, this tri-burner configuration outperformed the alternative setups. The spatial ratios between the burner walls (a:b, c:d, and e:f) were optimized to facilitate a uniform heat distribution across the drying layers within the chamber. Consequently, the heat flux was evenly dispersed, reducing the need for continuous ignition and enabling short, intermittent burner activation cycles to maintain the temperature effectively.

Figure 8 illustrates the variation of the measured parameter as a function of the operating condition for three different cases, represented by the gray, red, and blue curves. Overall, all three curves exhibit a decreasing trend, indicating that the measured parameter consistently declines as the independent variable increases. Among the three cases, the gray curve shows the slowest rate of decrease, maintaining comparatively higher values across the entire range. This behavior suggests a more stable performance or lower sensitivity to the changing operating condition.

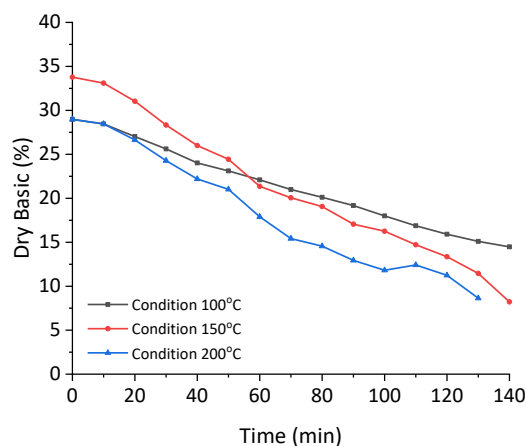


Fig. 8 Dry basic (%) of Charcoal briquette at 150°C drying.

In contrast, the red curve exhibits a moderate decline, initially maintaining higher values than the blue curve but converging toward lower values at higher operating levels. The blue curve demonstrates the steepest decline, particularly in the mid-to-late range, indicating the most pronounced reduction among the three cases. This sharper decrease implies that the corresponding condition is more sensitive to the operating parameter, leading to reduced performance or efficiency under more severe conditions. At lower operating levels, the differences between the three curves are relatively small, suggesting similar initial behavior. However, as the operating condition intensifies, the divergence becomes more apparent, highlighting the influence of system configuration or operating strategy on the measured response. Overall, the gray case provides the most favorable performance trend, while the blue case represents the least stable response over the evaluated range.

3.3 Material drying properties

Across all tests, 360 charcoal briquettes were arranged in 5 layers, with 72 briquettes per layer. The average combined mass of the five layers was 5 ± 0.5 kg, with each briquette weighing 0.13 ± 0.05 kg and possessing a dry mass of approximately 0.1065 kg. The drying trials were conducted until the moisture content approached the target standard of 8% (dry basis) [29].

The dry-basis moisture content during drying at 150°C initially ranged from 28% to 35%, reflecting the moisture introduced through charcoal preparation, mixing, and pressing. Biomass constituents can undergo transformation due to thermal exposure. In the torrefaction process, elevated temperatures in the range of $150\text{--}300^{\circ}\text{C}$ enhanced the grindability of the raw material. However, it remains an open question whether this improvement is attributable to the drying effects occurring within the lower temperature range of up to 150°C [30]. This moisture range is characteristic of briquettes produced in the case study and is suitable for the charcoal pressing and production processes used.

The method of arranging charcoal for drying significantly influenced the drying efficiency. Traditionally, farmers arrange briquettes in a tightly packed or overlapping manner, which restricts airflow between the blocks. This dense packing impedes air circulation across briquette surfaces, limiting moisture diffusion and evaporation, thereby prolonging drying time and causing uneven moisture removal. Furthermore, close contact between briquettes can facilitate moisture reabsorption when exposed to humid air currents.

In contrast, the case study implemented a grid-based drying layer arrangement that enhanced the surface area exposed to airflow. This configuration promotes a more efficient moisture exchange and vapor transfer. Additionally, maintaining appropriate spacing between layers ensures unobstructed air movement, preventing moisture entrapment and enabling uniform drying of those initiates from the bottom layer and progressing upward.

In addition to optimizing briquette design and arrangement to ensure uniform and efficient airflow, the drying temperature exerts a decisive influence on the drying kinetics, dramatically reducing the overall drying time. Empirical data show that lower temperature regimes slow moisture removal, whereas elevated drying temperatures accelerate the evaporation of water. For instance, thin-layer infrared drying experiments revealed that increasing the temperature from 80°C to 140°C reduced the time required to dehydrate biomass from ~92% to ~8.7% (dry basis) by more than two-thirds [31]. Moreover, studies on charcoal or biomass briquettes affirm that while compaction parameters have minimal impact, drying temperature dominates moisture reduction [32]. Kinetic modeling further corroborates that drying temperature significantly influences both the constant and falling rate phases of moisture removal in biomass particles [33]. This is bolstered by the findings that 150°C often emerges as an optimal drying temperature, balancing efficiency and product quality in briquetting operations [33]. Specifically, in our experiments, drying at 150°C reduced the charcoal briquette moisture to approximately 8% (dry basis) within approximately 140 min, highlighting this temperature range as particularly effective for accelerated, high-quality drying.

The evaluation of energy consumption for heating the drying oven revealed that the system design, which incorporates an automatic gas ignition mechanism controlled by a PID controller, significantly influences both heat generation and fuel utilization. LPG consumption during the drying process varied with temperature: drying at 100°C consumed approximately 3.7 kg of fuel, at 150°C consumed 1.5 kg, and at 300 °C consumed 2.4 kg. The elevated fuel usage at 100 °C was primarily attributed to the temperature regulation and ignition dynamics inherent to the control system. Although the system can supply heat for short intervals at this temperature, the tri-burner automatic ignition design necessitates the simultaneous ignition of all three burners at startup by applying a high-voltage spark to ignite the LPG. The relatively large burner size led to substantial fuel consumption during ignition. If ignition fails, the system automatically cuts off the fuel supply to the affected burner. Notably, 100°C is near the lower operational threshold for infrared burners, resulting in frequent ignition cycles to maintain the temperature. Additionally, the high initial moisture content of the charcoal briquettes exacerbated this inefficiency, rendering this temperature range suboptimal for the infrared burner system. Drying at 150°C demonstrated greater fuel efficiency and operational suitability than drying at 200 °C. Although both temperatures achieved a final dry-basis moisture content of approximately 8% within similar drying durations and yielded comparable charcoal quality, the LPG consumption at 200 °C exceeded that at 150 °C by approximately 0.7 kg. These data underscore the efficacy of employing an LPG-fueled infrared burner system for optimally drying charcoal briquettes at 150 °C.

4. Conclusion

The development of a 50 kg high-temperature dryer for charcoal briquettes, incorporating infrared burner heating and electronically controlled temperature regulation, markedly improved drying efficiency and reduced processing time. Operational parameters were carefully optimized based on the thermal and moisture characteristics of charcoal, targeting a final moisture content below 8% to comply with industry standards. Experimental results demonstrated that the five-layer drying chamber design promoted uniform heat distribution and enhanced internal airflow, ensuring thorough and consistent moisture removal throughout all layers. The drying sequence commenced at the bottom layer and progressed systematically upward, allowing gradual and controlled evaporation. Among the various conditions tested, maintaining a chamber temperature of 150 °C provided optimal performance, achieving a balance between efficient drying duration and minimal specific fuel consumption. This temperature condition not only reduced energy input requirements but also maximized production throughput, contributing to overall operational efficiency. By combining precise temperature control, strategic airflow design, and sequential layer drying, the system ensures high-quality briquettes with consistent moisture content, while simultaneously improving energy utilization and productivity in commercial-scale charcoal briquette production. Based on the findings of this study, it is recommended that drying systems be given greater consideration in the industrial production of charcoal briquettes, rather than relying solely on low-cost or natural drying practices. Although conventional approaches aim to minimize or eliminate drying-related costs, they often lead to extended processing times, production bottlenecks, and missed commercial opportunities, particularly in the context of the rapidly expanding briquette market. The results demonstrate that the developed drying system, despite incurring additional fuel-related operational costs, offers a clear advantage by significantly reducing drying time and enabling briquettes to achieve market-ready moisture levels more efficiently. This improvement allows for immediate packaging and distribution, enhances production continuity, and increases overall throughput. Therefore, future briquette production facilities and system upgrades should prioritize controlled and accelerated drying technologies to improve economic performance, production reliability, and competitiveness. Further studies are also recommended to evaluate the long-term economic feasibility and scalability of the proposed drying system under commercial operating conditions.

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